NsG-269-62

OTS PRICE

XEROX $ 1.60ph

MICROFILM $ 0.80mf

11p.

(NASA Grant NsG-269-62)

SOLAR COSMIC RAY PROPAGATION CHARACTERISTICS N64 13183

by

K. G. McCracken

Southwest Center for Advanced Studies

Dallas, Texas

8100002

CODE-1

(NASA CR-55150)

OTS: $1.60ph, $0.80mf

[1963] 11p refs

Of late years, our knowledge of solar flare production of cosmic rays has increased greatly. This is primarily due to our recently acquired ability to observe cosmic rays in the energy range 5Mev - 500 Mev. Not only does this extend the range over which spectral data can be obtained, it also results in a much greater sample of cosmic ray flare effects from which to draw inferences. Furthermore, the energy range has become large enough to permit study of whether particle rigidity, velocity, or energy are the important quantities in describing the properties of the solar cosmic rays, and also to determine the manner in which time changes are functions of energy (or equivalent parameter).

It is the purpose of this paper to summarise the various properties of solar cosmic radiation established from these, and earlier data, and to inquire as to the adequacy of current models to explain the observed phenomena.

(2)

1. STATISTICS OF OCCURRENCE

D Conf.

Restricting our attention to particle energies >500 Mev, the observation of solar cosmic rays after a solar flare is found to be heavily biased towards flares which occur on the western portion of the solar disc. It is observed that those cosmic ray flare effects for which the parent flare occurs on, or near the western limb of the sun,

1) exhibit the most rapid rise to maximum intensity; 2) exhibit the most intense anisotropies; 3) exhibit, on the average, the greatest particle fluxes; 4) exhibit very short flight times for the sun to earth journey of the cosmic rays and, 5) on those occasions for which the data have been good enough, the first cosmic rays have been observed to arrive at the earth from a direction some 50 to 60° to the west of the earth-sun line, and roughly in the plane of the ecliptic. All these facts have led to the picture that lines of force of the interplanetary magnetic field stretch in a relatively well-ordered fashion from near a sunspot which is near the western limb to the vicinity of the earth; thereby providing an easy route for the cosmic rays to follow in order to reach the earth. (See Figure 1) The fact that this postulated field configuration is in general agreement with the concept that the solar wind will stretch out the solar magnetic fields to form lines of force in the form of an Archimedes spiral adds credence to this model.

On the basis of the above model one can argue that, as one goes to lower particle energies, so will the gyroradius of the cosmic ray particle decrease;

For presentation at the Intern. Conf. on Cosmic Rays, Jaipur, India Submitted for Publication

consequently the magnetic moment of the gyrating particle will be more nearly constant with time, and consequently, the strong bias towards the western limb, and in addition the properties 1) to 5) above will become even more pronounced. The available evidence indicates that this is not so. For example, the observations of marked p.c.a., that is, large fluxes in the 5-30 Mev range, and the observations with balloons, show that the low energy flare effect is only very slightly biased towards the western portion of the solar disc. See Figure 2 (after C. W. Warwick). It would appear that the mode of propagation of these low energy particles is different from that of the high energy particles.

2. TIME HISTORY

Considering the idealised case of isotropic diffusion away from an impulsive, point source, into an infinite medium, Parker, (and others) has shown that the unidirectional intensity at a point distance R from the source, at time t after the injection is given by

$$I(R,t) = \frac{N\beta c}{32\pi\left(\frac{\beta c \lambda \pi t}{3}\right)^{3/2}} \exp\left(-\frac{3R^2}{4\beta c \lambda t}\right)$$

where N is the number of particles injected by the source, and λ is the mean free path. Consequently, a plot of ln $\left\{ I\ (R,t)\ .\ t^{3/2} \right\}$ versus 1/t, for a given value of β (particle velocity in units of c) , should be a straight line.

Recently, the Goddard group, using data from Explorer XII, and the Minneapolis group, using balloon data, have studied a number of well observed flare effects, and have found that, after an initial period of about one hour has elapsed (during which time anisotropies are evident), the above quantities are linearly related for an appreciable portion of the flare effect. See Figure 3. That is, even though in the case of the September 28, 1961 flare effect the cosmic ray times of flight and anisotropies are suggestive of direct magnetic connection to the vicinity of the parent solar flare, the evidence also suggests that the lower energies in particular suffer considerable diffusion en route to the earth. If this diffusion were occurring only in the immediate vicinity of the sun there should still be an appreciable anisotropy observed at the earth as long as there was leakage of the cosmic rays from the "reservoir" in the vicinity of the sun: - a prediction not verified by observation. We must, therefore, seek a model which can preserve the properties of "quick access" for some particles; "diffusion access" for the majority; and negligible anisotropy at the earth after about the first hour of the cosmic ray flare effect.

Considering the decay phase of flare effects, Meyer et al from consideration of the February 23, 1956 flare effect; and other workers, from consideration of various balloon data (vide infra) have shown that sometimes the intensity decreases roughly at $t^{-3/2}$, as predicted by the classical diffusion theory. At other times, the decay is more accurately an exponential in time: - this being the type of decay predicted if the diffusing medium is not infinite,but bounded, an exponential decay of intensity commencing once particles start to be lost through the boundary. That is, the decay phases of many flare effects suggest that the cosmic rays are leaking out of the region into which they are initially injected in a manner not unlike that predicted by classical diffusion theory.

To preserve the "direct access" property, and yet obtain a diffusion-like propagation in the large, one may consider a model similar to that in Figure 4. The irregularities in the lines of force result in an anisotropic diffusion:- the cosmic rays diffusing across the lines of force, while moving essentially freely along them. An alternate possibility suggested by Parker is that the cosmic ray particles may, in the process of being reflected from the boundary (past the orbit of earth), diffuse from one tube of force to another. This will be discussed later.

The very extensive observations made by the Goddard group using detectors on Explorer XII yield further information regarding the diffusion mode of access to the earth. They find that, plotting intensity against β t, where t is the time after the flare effect, the various curves are identical in shape (and superposable after normalization). This indicates that the particles of different energy have travelled essentially the same distance in reaching the earth. Interpreted as a classical diffusion process, this would indicate a mean free path which is independent of β .

3. ENERGY SPECTRUM

Looking at restricted energy intervals, and one type of particle (usually protons), the energy spectra could often be fitted by either power, or exponential laws in either energy or rigidity. Once data from a larger energy range became available, however, a critical test was possible to determine which type of spectral law was the simplest fit to the data. Furthermore, consideration of particles of different A/Z ratio also permitted determination of the spectral law. Freier and Webber in this manner decided that over the energy/nucleon range from ≈ 2 Mev - 5 Bev, the differential spectrum fairly late in a flare event is described by an exponential law in rigidity (P) given by

$$j(P,t) = j_1(t) \exp\{-P/P_0(t)\}$$

where $j_1(t)$ and P_0 (t) are functions of time. Generally, as time increases, $P_0(t)$ decreases, the data still being well described by an exponential. This preservation of an exponential law places restrictions on the rigidity and temporary changes which may occur in j_1 (t) .

Figure 5 (Freier and Webber) and Figure 6 (derived from data presented by Biswas et al) illustrate the types of spectra to be observed. The wide variation in P_0 is to be noted.

The Goddard emulsion group has made a careful study of the proton, alpha and medium particle fluxes in a number of flare effects. They note that, if the fluxes of particles of different A/Z are known, the dominant quantity, (i.e. rigidity, velocity, etc.) in the determination of the decay of the radiation intensity can be determined. Thus they find that for the November 12, 1960 event the ratio of the proton and alpha fluxes in the same range of energy/nucleon is invariant with respect to time, indicative of a decay which is velocity dependent (and not rigidity dependent: - if rigidity dependent, the ratio would vary with time). See Figure 7. On the other hand, the decay for the November 15, 1960 event was apparently rigidity dependent. See Figure 7. A velocity dependent diffusion at energies 1 Bev has been predicted by Parker on the basis of scattering of cosmic rays by magnetic inhomogenieties.

4. BASIC FACTS TO BE ACCOMMODATED IN MODEL

In summary, any model must explain the following observed features of cosmic ray flare effects.

a) At high energies - bias towards western limb of sun.
   At low energies - bias to centre of solar disc.

b) Rapid access to the earth of some cosmic rays. Marked anisotropies (short-lived) oriented some 60^o to the west of the sun. Some scattering of particles does occur en route to the earth.

c) Diffusion-like access of large majority of particles.

d) Few flare effects are attributable to flares on back-side of sun.

e) The mechanism responsible for the Forbush decrease can trap solar cosmic rays (e.g. November 12, 1960).

f) The spectrum is frequently a good approximation to an exponential in rigidity, the characteristic exponent P_o being a function of time.

g) The decay of flare effect often follows a law similar to that given by classical diffusion. The diffusion mean free path is sometimes independent of rigidity.

Some models will be discussed.

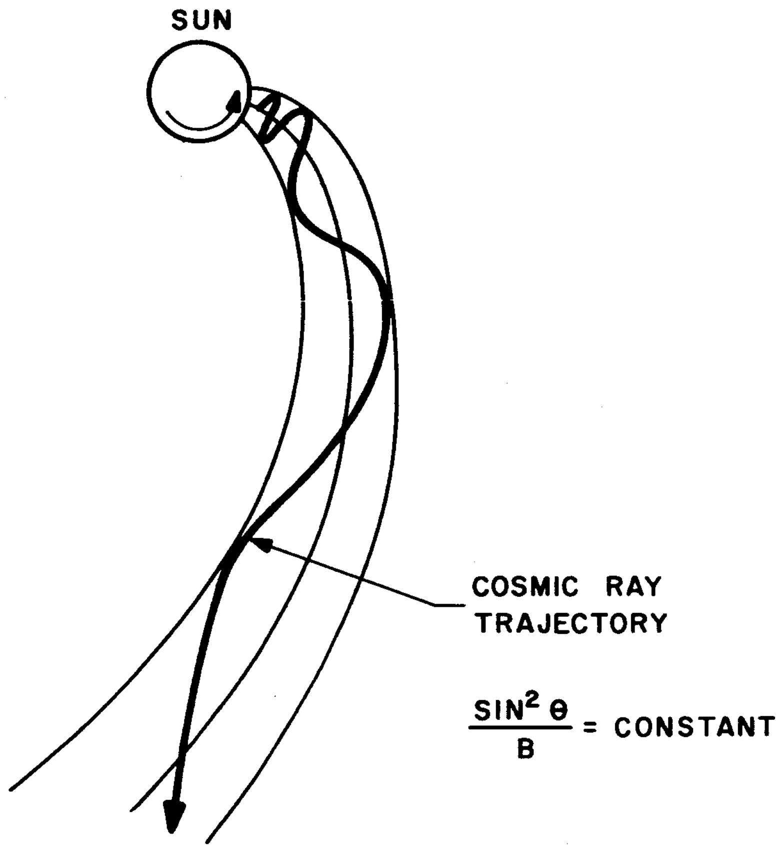

SUN
COSMIC RAY
TRAJECTORY
$\frac{\text{SIN}^2\,\theta}{\text{B}}$ = CONSTANT

FIGURE 1

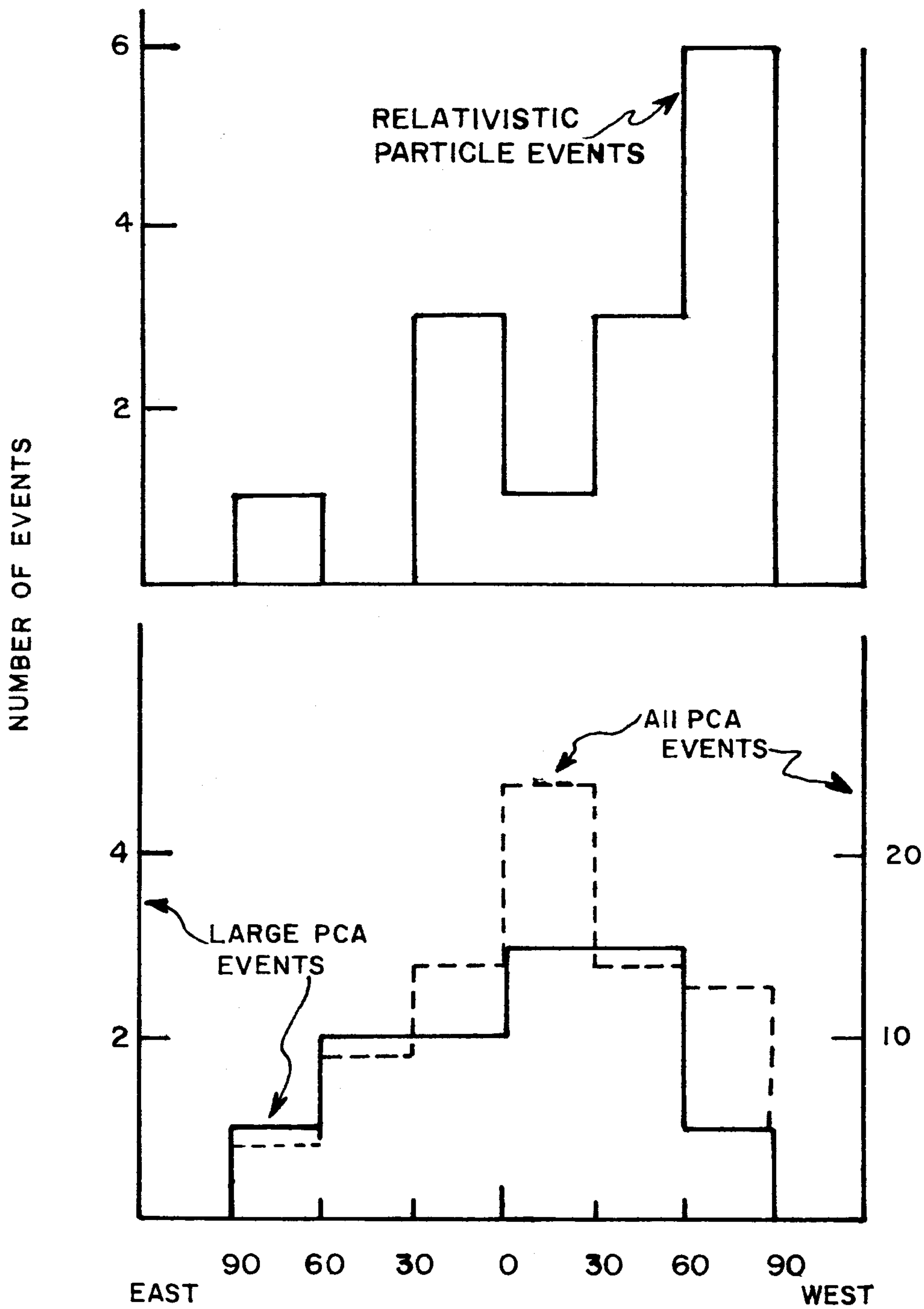

6
4
2
RELATIVISTIC
PARTICLE EVENTS
NUMBER OF EVENTS
All PCA
EVENTS
4
2
20
10
LARGE PCA
EVENTS
90 60 30 0 30 60 90
EAST
WEST
SOLAR LONGITUDE

FIGURE 2

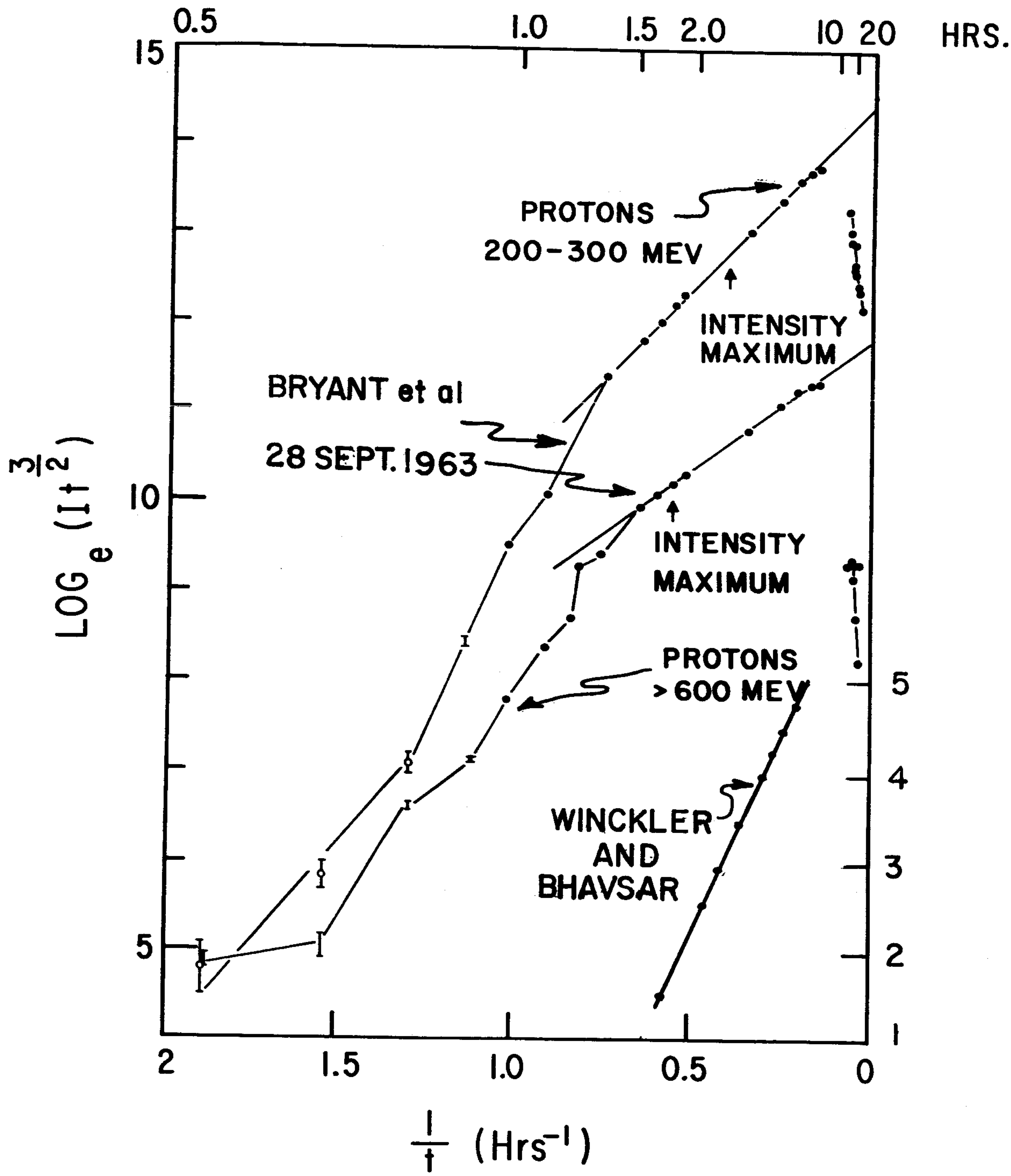
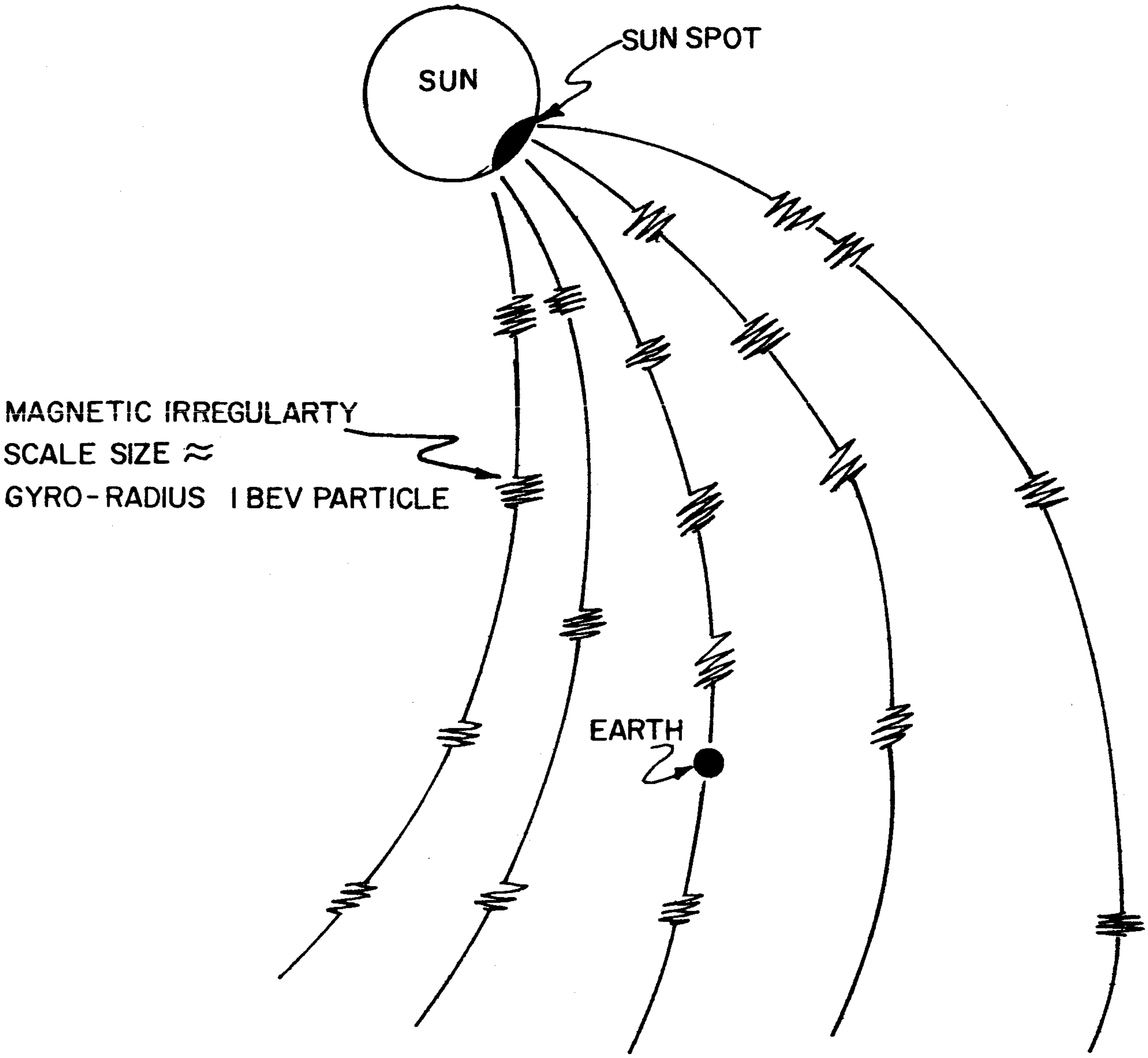
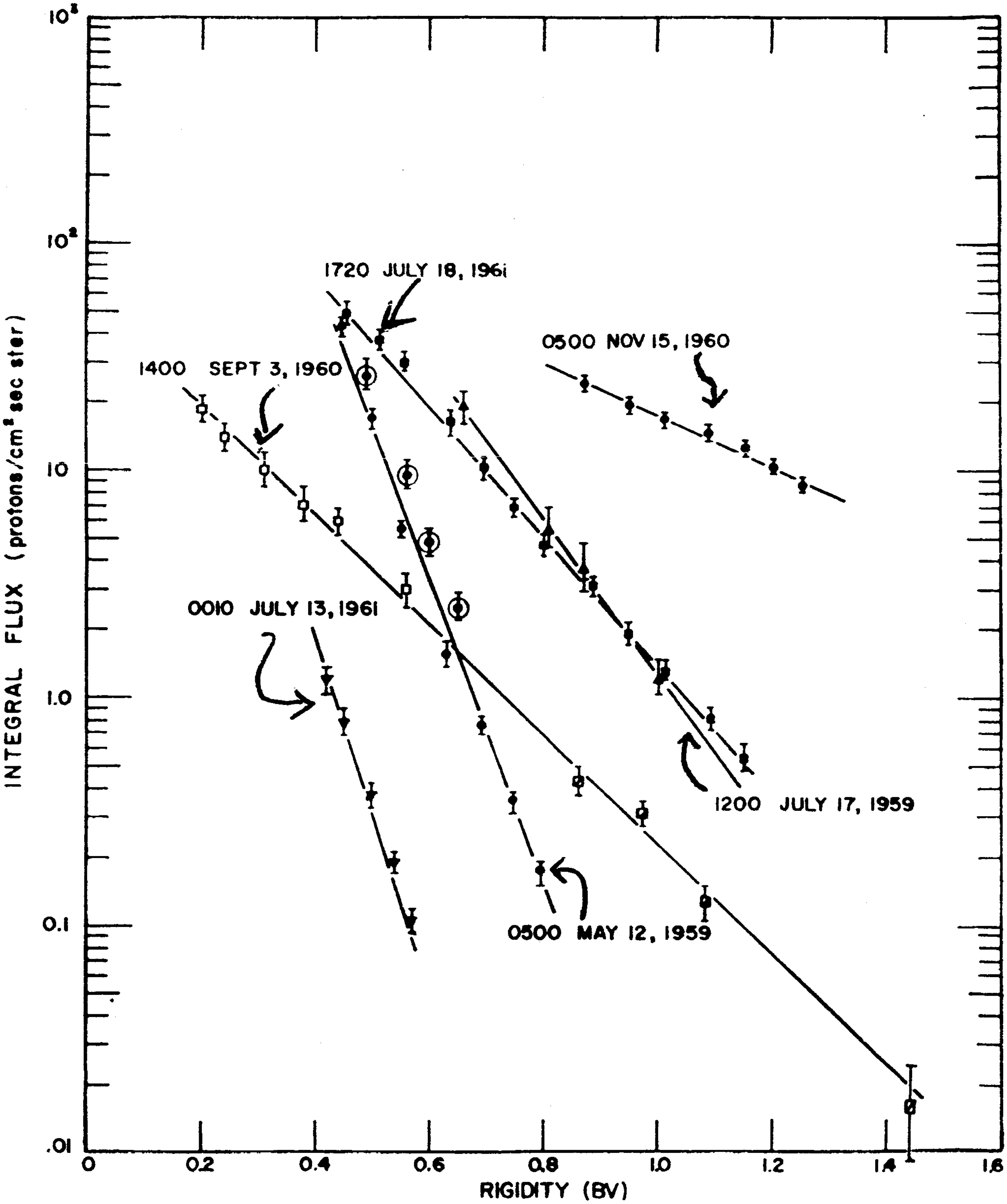

0.5
1.0
1.5
2.0
10
20
HRS.
15
10
5
$\mathrm{LOG}_e\,(It^{\frac{3}{2}})$
PROTONS
200-300 MEV
INTENSITY
MAXIMUM
BRYANT et al
28 SEPT. 1963
INTENSITY
MAXIMUM
PROTONS
> 600 MEV
WINCKLER
AND
BHAVSAR
5
4
3
2
1
2
1.5
1.0
0.5
0
$\frac{1}{t}$ (Hrs^{-1})

FIGURE 3

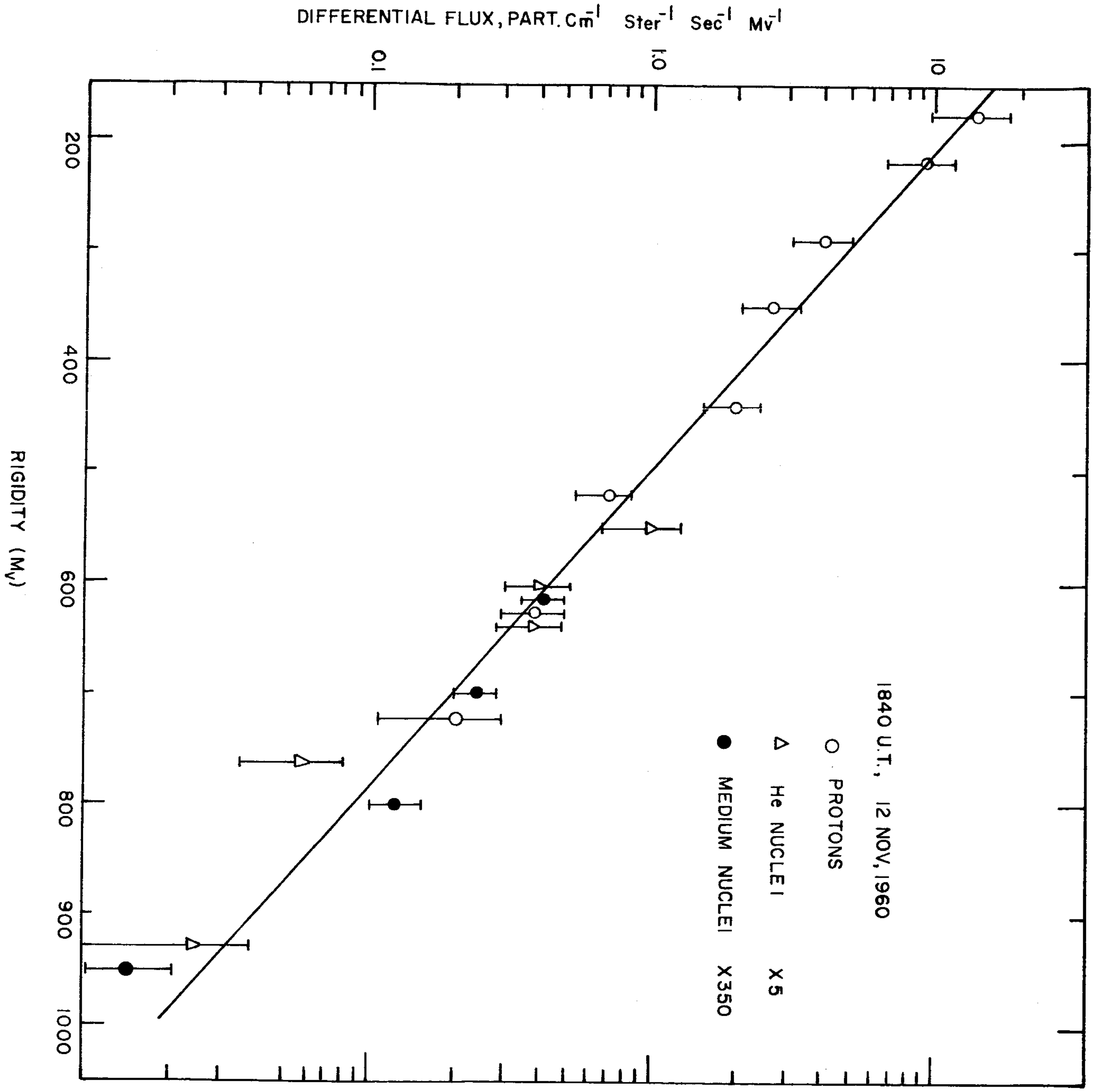


PARTICLES PREVENTED FROM
ESCAPING TO INFINITY

FIGURE 4



10³
10²
10
1.0
0.1
.01
INTEGRAL FLUX (protons/cm² sec ster)
1720 JULY 18, 1961
0500 NOV 15, 1960
1400 SEPT 3, 1960
0010 JULY 13, 1961
1200 JULY 17, 1959
0500 MAY 12, 1959
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
RIGIDITY (BV)



DIFFERENTIAL FLUX, PART. Cm^{-1} Ster^{-1} Sec^{-1} Mv^{-1}
0.1
1.0
10
RIGIDITY (M_v)
200
400
600
800
900
1000
1840 U.T., 12 NOV, 1960
PROTONS
He NUCLEI X 5
MEDIUM NUCLEI X350

FIGURE 6

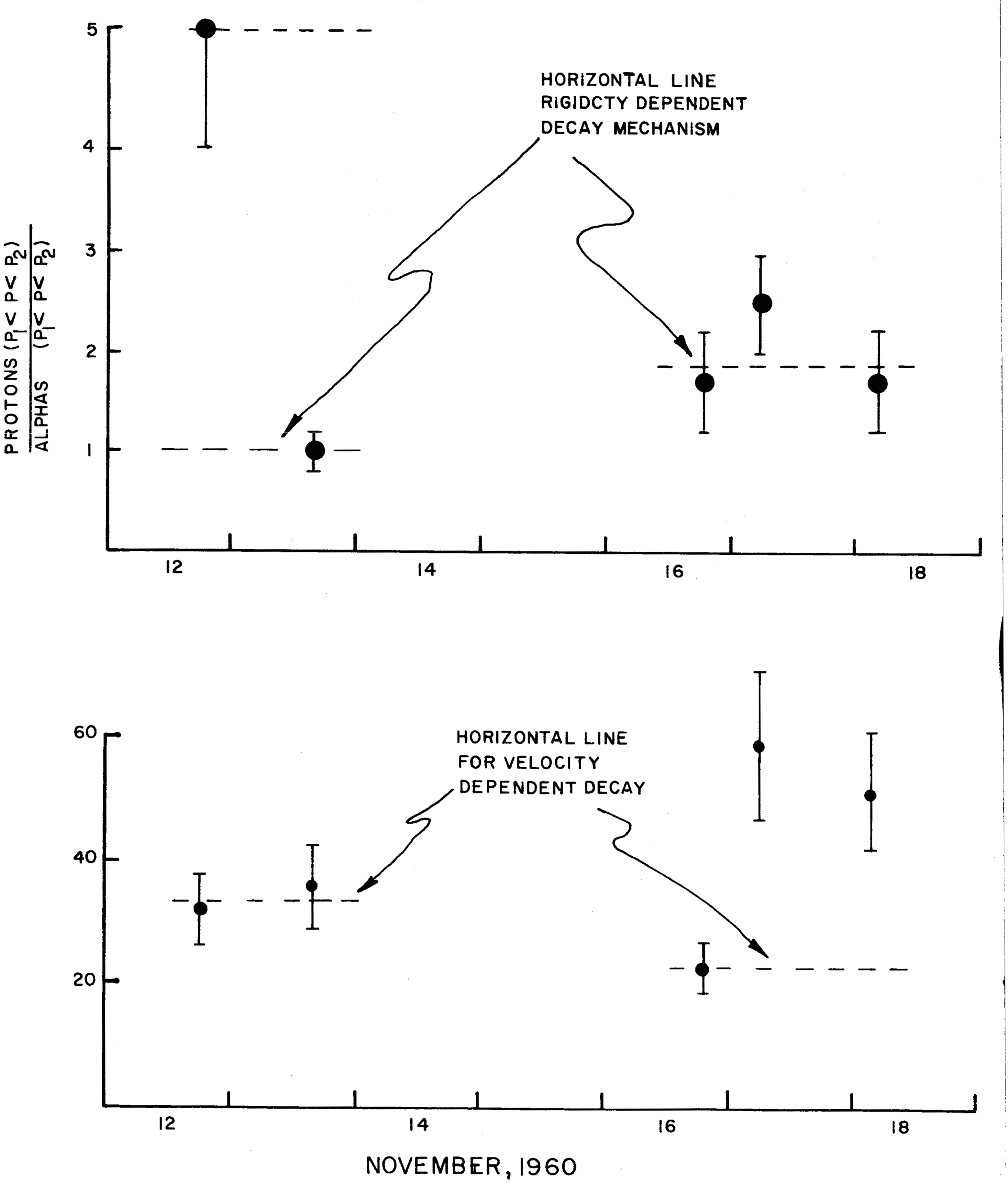

PROTONS (P1 < P < P2) / ALPHAS (P1 < P < P2)
HORIZONTAL LINE
RIGIDCTY DEPENDENT
DECAY MECHANISM
HORIZONTAL LINE
FOR VELOCITY
DEPENDENT DECAY
NOVEMBER, 1960

FIGURE 7